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A soft x-ray undulator is to be based at the vacuum ultra-violet storage ring at the National Synchrotron Light Source. The undulator will be used as a radiation source by a multi-institutional research team to perform the first spin-polarized photo-emission experiments in the United States to study novel ultra-thin magnetic films and surfaces.

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ANNUAL REPORT:

December 1987 - March 1989

SOFT X-RAY UNDULATOR

S. D. Bader

Materials Science Division
Argonne National Laboratory
Argonne, Illinois 60439

Office of Naval Research Contract #N00014-87-F-0022

MFEL Program

Strategic Defense Initiative Organization

This is the second annual report for a two-year program to base a soft x-ray undulator at the vacuum ultra-violet (VUV) storage ring at the National Synchrotron Light Source (NSLS). The undulator will be used as a radiation source by multi-institutional research teams to perform the first spin-polarized photoemission experiments in the United States. The undulator source will permit major advances to take place in materials research in the forefront area of novel, ultra-thin magnetic films and surfaces.

The activities are summarized on the attached bulletized "Chronology of Activities". The two most important achievements are that contracts have been negotiated both for the undulator and vacuum chamber that the undulator encases. The undulator contract was awarded to Spectra Technology, Inc. (STI), a subsidiary of Spectra Physics, located in Bellevue, Washington. Progress reports submitted by STI are appended to this report. Included is a timetable that shows the undulator installation on the NSLS VUV ring as taking place during the scheduled February, 1991 shutdown of the ring.

The vacuum chamber is being fabricated by NSLS. STI and NSLS have been coordinating their activities to make the installation successful.

Plans are underway at Argonne to design a methodology for testing the undulator performance on the VUV ring. It will include monitoring the characteristics of the high-harmonic radiation output, because of its sensitivity to the magnetic design errors. Comparisons will be made to the performance of other insertion devices, with the hope that the data will permit future device design to benefit from past experience.

A preprint is attached of a manuscript submitted to the Review of Scientific Instruments. The manuscript is based on a presentation by P. J.

Viccaro at the Synchrotron Radiation Instrumentation Conference in Tsukuba, Japan, last year.

Also attached to this report is the preface to the Conference proceedings of the meeting entitled "Vacuum Design of Advanced and Compact Light Sources". In the preface S. D. Bader is acknowledged for inspiring the highly successful international meeting. The inspiration was derived from participation in the SDIO/MFEL Program.

Chronology of Activities

January 1988	• Spectra Technology, Inc. (STI) is chosen by Argonne National Laboratory (ANL) Source Selection Board for undulator contract negotiation.
March 1988	• Optical Society of America Conference "FEL Applications in the VUV" - Cloudcroft, NM.
April 1988	• Defense Contract Audit Agency Report on Review of STI Preaward Subcontract Price Proposal.
May 1988	• SDIO/MFEL Contractors Meeting - Salt Lake City.
September 1988	• Start date for STI undulator contract.
	• Proposal submitted to MFEL Program on "Novel, Ultrathin Magneto-Optical Devices".
October 1988	• Review of Scientific Instruments manuscript submitted on "Soft X-ray Undulator for U5 Beamline at NSLS".
	• STI Central Field Magnetic Design Review at ANL.
November 1988	• Site visit to NSLS with STI Personnel.
January 1989	• Tour of Boeing Physical Sciences Research Center FEL facility.
	• Undulator preliminary design review at STI.
	• Undulator vacuum chamber contract with NSLS finalized.
March 1989	• Internal document submitted to ANL Advanced Photon Source Division on "Procurement History of the Hybrid Undulator for the U-5 beamline at NSLS".

ANL Contract No.: 82282401

STI Control No.: 1433

U-5 PERMANENT-MAGNET HYBRID UNDULATOR

Monthly Progress Report

15 November 1988 - 15 December 1988

The central magnetic field design was completed during this time frame, and presented to ANL and NSLS personnel, and approved. The Requests for Quotation for the magnets and poles were released, and responses from possible suppliers are expected the first part of January 1989. The conceptual design is proceeding rapidly and the support system, magnetic structure, and gap separation drive train system are all making progress toward completion. Specifications for the stepper motor controllers and drivers were received from NSLS and are being incorporated into the design. All work is being directed toward the completion of the preliminary design and its review on 17 January 1989.

U-5 Central Magnetic Design Review Summary

22 November 1988

Argonne National Laboratory

The following is a summary of the conclusions jointly agreed upon by representatives from Argonne National Laboratory (ANL) Brookhaven National Laboratory (BNL), and Spectra Technology, Inc. (STI) during the review of the U-5 undulator central magnetic field design.

The design for the magnets and poles was agreed upon by all present (ANL, BNL, and STI). STI is to proceed as quickly as possible with issuing the Requests for Quotation (RFQ) for both the NdFeB magnets and the vanadium permendur pole material. A copy of both RFQs will be sent to ANL at the time they are released. It was determined that the magnets would be preferred in a single piece structure rather than in multiple pieces, and that the magnets should have an appropriate surface treatment to impede corrosion. STI will examine the quotations that are submitted for the magnets and make a recommendation for the best source. Final discussion and vendor selection will be made at the preliminary design review. STI will proceed with the bid and procurement cycle for the vanadium permendur directly. This keeps the poles and their manufacture from becoming a pacing item in the schedule.

In addition to the agreement on the magnetic design some other items were discussed and agreed on which impact more directly the mechanical design as opposed to the magnetic design. It was decided that the use of two motors for the drive system would be acceptable, and in fact preferred. Each motor will operate the separation system for either the upstream or downstream support. Likewise additional information on the operation of the U-5 undulator at the optional reduced (24 mm) gap will be forwarded from STI to all of the participants.

The date for the preliminary design review was fixed as 17 January 1989 at Spectra Technology's facilities in Bellevue, WA.

The following were in attendance at the U-5 Magnetic Design Review: Sam Bader, ANL-MSD; Anne-Marie Fauchet, BNL-NSLS; Suk Hong Kim, ANL-APS; Tom Klippert, ANL-APS; Kem Robinson, STI; Gopal Shenoy, ANL-APS/MSD; Lorraine Solomon, BNL-NSLS; and P. James Viccaro, ANL-APS/MSD.

Sam Bader

Dr. Sam Bader
Technical Representative
for Argonne National Laboratory

Kem Robinson

Dr. Kem Robinson
Technical Representative
for Spectra Technology

ANL Contract No.: 82282401

STI Control No.: 1433

U-5 PERMANENT-MAGNET HYBRID UNDULATOR

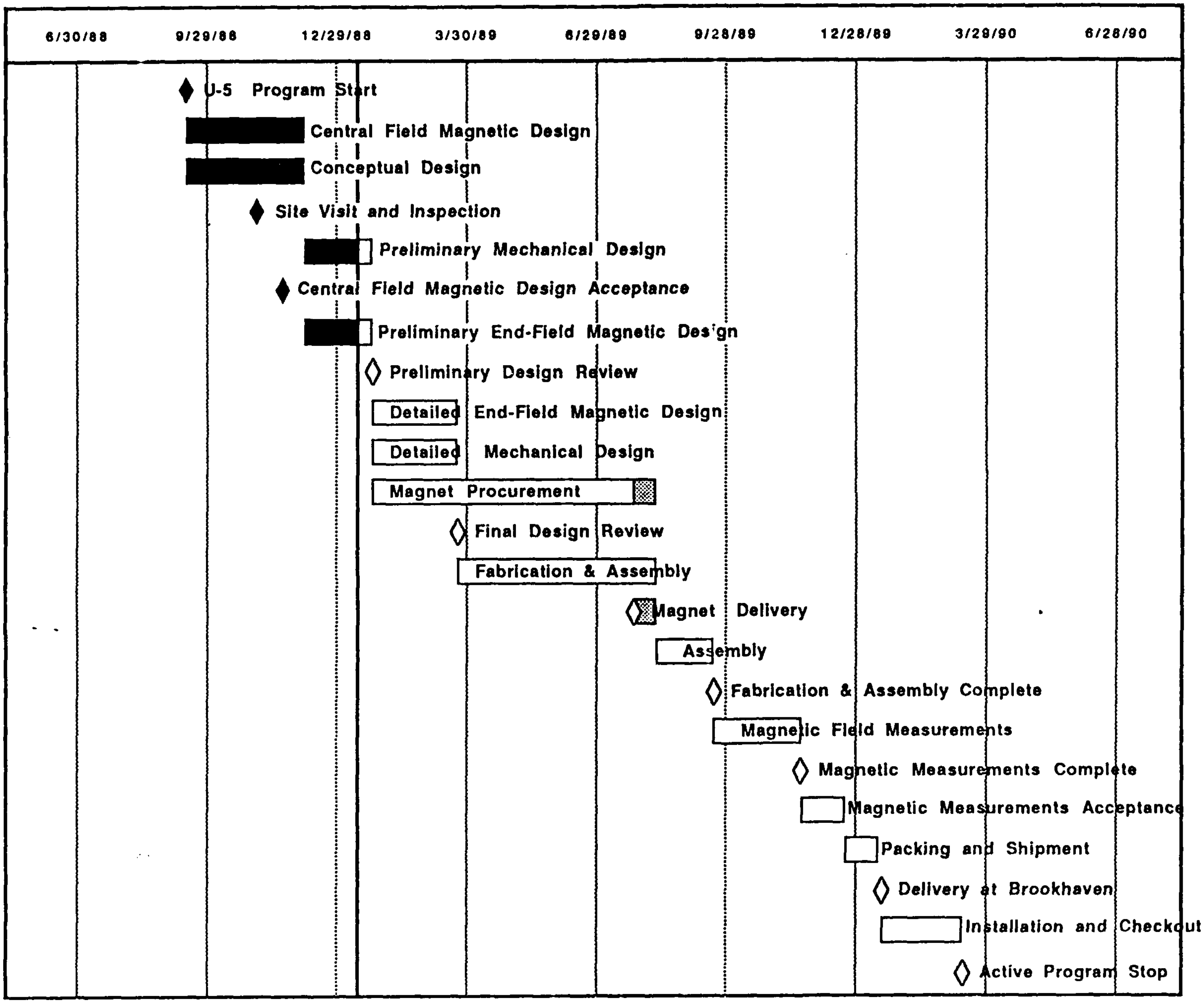
Monthly Progress Report

15 December 1988 - 15 January 1988

The quotations for the magnets and poles were received from possible suppliers and a preliminary selection was made. The conceptual design is completed: the support system, magnetic structure, and gap separation drive train system. All work was directed toward the completion of the preliminary design and its review on 17 January 1989. Attached is an updated timeline of the project.

U-5 PERMANENT-MAGNET HYBRID UNDULATOR SCHEDULE

15 October 1988



ANL Contract No.: 82282401

STI Control No.: 1433

U-5 PERMANENT-MAGNET HYBRID UNDULATOR

Monthly Progress Report

15 January 1989 - 15 February 1989

The preliminary design review was completed at the beginning of this time period and detailed design has begun in earnest with the magnetic structure and drive train systems nearing completion. Input from Brookhaven is still required in several areas, and the need for this information will soon become critical to the progress of the program. Arrangements were made to stagger the final design review so that more efficient use of the resources and fabrication schedules can be exploited to progress the design. During the month of January approximately 600 man-hours were expended on this project principally in a mixture of engineering and designer/drafting again underscoring the emphasis on the detailed design at this point.

A Soft X-Ray Undulator for the U5 Beamline at NSLS*

P. J. Viccaro, G. K. Shenoy and S. H. Kim
Advanced Photon Source, Argonne National Laboratory, Argonne, IL 60439

and

S. D. Bader
Materials Science Division, Argonne National Laboratory, Argonne, IL 60439

October 1988

bsm

This paper submitted to the American Institute of Physics.
Rev. Sci. Instru.

*This work supported by the U.S. Department of Energy, BES-Materials Sciences, under contract no. W-31-109-ENG-38.

A Soft X-Ray Undulator for the U5 Beamline at NSLS*

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and

S. D. Bader
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Abstract

The magnetic structure and spectral properties of a 7.5-cm, 30-period hybrid undulator are described. The device will be installed at the U5 port of the VUV storge ring at Brookhaven National Laboratory and will be a tunable source of very high brillance soft x-ray radiation over the range of 13 from approximately 150 eV.

*This work supported by the U.S. Department of Energy, BES-Materials Sciences, under contract no. W-31-109-ENG-38.

1. Introduction

A tunable hybrid undulator to be installed at the U5 port of the VUV ring at the National Synchrotron Light Source (NSLS) is in the final stages of its design. Construction of the device is expected to be completed by the end of early 1989. The undulator will cover the spectral range from approximately 13 to 150 eV using the first and third harmonic radiation and will be a high brightness source of soft x-rays.

The unique spectral characteristics of this undulator source in terms of its tunability, intensity and temporal structure will provide excellent research opportunities in a variety of areas. These include spin-polarized photoelectron spectroscopy of novel magnetic surfaces, molecular photophysics of shape and autoionizing resonances, and time-resolved spectroscopic and scattering studies to monitor surface chemical reactions and interface phenomona.

In the following, some aspects of the design of the magnetic structure of the undulator are presented as well as results of calculations of the expected spectral properties which explicitly include the emittance properties of the VUV storage ring.

2. Magnetic Design

The transverse undulator has a hybrid magnet configuration in which the field quality is much less dependent on the manufacturing tolerances of the permanent magnet materials than in Halbach's original pure REC design.[1] The device uses Nd-Fe-B magnets and vanadium permendur pole tips. The design is based on an optimization procedure in which the geometrical parameters of the structure are varied in two-dimensional (PANDIRA[2]) and three-dimensional[3] field computations. The resulting parameters are presented in Table 1.

Three-dimensional effects are estimated in order to obtain the pole and magnet width and overhang necessary to obtain the required horizontal field homogeneity and to reduce flux loss.[4]

TABLE 1
Magnetic Specifications of the U5 Hybrid Undulator

Total Length (m)	2.25
Period Length (cm)	7.5
Magnet Material	Nd-Fe-B
Coercive Force (kOe)	$\gtrsim$ 10.6
Pole Material	Vanadium Permendur
Minimum Gap (cm)	3.4
Peak Field (T)	0.42
Pole Width (cm)	>7.5
Pole Overhang (mm)	1
Magnet Width (cm)	$\gtrsim$ 10.7
$\Delta B_{rms}/B$	< 0.01 on centerline
Harmonic Content of Field	< 2%
Residual Steering Errors	$\gtrsim$ 100 G-cm vertical
Sextupole Error	$\gtrsim$ 100 G/cm
Phase Error ($\Delta\lambda/\lambda$)	0.008 on centerline

Figure 1 shows a two-dimensional cross section of the upper half of the magnetic structure including the end-pole configuration. Also shown are the magnetic flux lines from the PANDIRA calculations at the minimum gap of 3.4 cm. The pole overhang in the vertical (y) direction is 1 mm and the pole thickness is 1.40 cm. The magnet overhang in the horizontal (x) direction is 1.6 cm, which minimizes the field roll-off and reduces flux losses in this direction.

The estimated peak-field value of 0.42 T at the closed-gap setting assumes a coercive force for the Nd-Fe-B of -10.6 kOe and also a finite magnet width. The expected harmonic content of <2% (see Table 1) in the field along the longitudinal direction is determined primarily by the pole thickness (1.4 cm) compared to magnet thickness.

The end-pole configuration shown in Fig. 1 consists of a modified magnet-block arrangement preceeding the last pole piece in which a half-thickness portion of magnetic material is removed. In addition, a half-thickness magnet piece of approximately 40% of the standard magnet height is installed between the end pole and end-field clamp. In this arrangement, the height of the last piece is adjusted in order that the field integral is approximately zero for the device at closed gap. Additional electromagnetic compensation is proposed to be included if necessary and can be installed in a space between the field clamp and end pole. A plot of the on-axis magnetic field due to the end compensation is shown in Fig. 2. The end-field terminates to zero in approximately 14 cm.

3. Spectral Properties

As mentioned, the undulator will be tunable in energy. This will be accomplished by changing the value of the magnet gap and hence magnetic field of the device so as to set the position of the fundamental or third harmonic at the required energy. The on-axis energy of the odd harmonics, E_j, is given by[5]

$$E_j = 0.949jE_r^2/(\lambda_o(1+K^2/2)) \tag{1}$$

where E_r is the ring energy in GeV, j is the harmonic number (1,3,5...), λ_0 is the undulator magnetic period in cm, K is the deflection parameter given in terms of λ_0 and peak on-axis magnetic field, B_0, by:

$$K = 0.934\lambda_0 B_0 \tag{2}$$

For the hybrid geometry, the field has an approximate exponential-like dependence on the gap and, therefore, K and consequently E_j are functions of the gap. For the minimum gap of 3.4 cm and a ring energy of 0.75 GeV, the fundamental occurs at approximately 13 eV with a K-value of 2.9. At the open gap position, with K=1, the fundamental occurs at approximately 50 eV. With these K-values, excellent spectral intensity will be available at the third harmonic and consequently, the combined fundamental and third harmonic tunability range will be 13 to approximately 150 eV.

The actual spectral intensity as a function of x-ray energy has been calculated using a Monte Carlo numerical code which take the electron beam emittance into account. The VUV-ring parameters used are given in Table 2. Figure 3 show the on-axis spectral brilliance of the device in (ph/s/0.1%BW/ $mrad^2 mm^2$) as a function of photon energy for the minimum gap with K=3 and the open gap of approximately 6 cm where K=1. At ring currents of 750 mA, a spectral brilliance above 10^{16} is expected at the harmonics over the tunability range. Quite sizable second on-axis harmonic radiation is also observed at all the gap settings due to the finite size and divergence of the electron beam.

TABLE 2

Electron beam parameters for the VUV ring used in the calculation of the spectral properties

Ring Energy	0.750 GeV
Stored Current	750 mA
Horizontal Emittance	90 nm-rad
Vertical Emittance	0.9 nm-rad
Horizontal Betatron Function	11.6 m
Vertical Beatatron Function	5.5 m

The spectral brilliance for the fundamental and third harmonic is shown in Fig. 4 over the tunability range expected for the device. These results indicate that high brilliance (and hence spectral intensity) exceeding 10^{16} ph/s/0.1%BWmrad^{2}mm^2 can be achieved over the tunable photon energy range of 13 to 150 eV. This represents a usable tunability interval which is a factor of ten times the minimum fundamental energy possible.

At the odd harmonic energies, the spatial distribution of the radiation for the case of zero particle beam emittance consists of a central intense radiation cone surrounded by rings of weaker intensity. The angular width of the central cone is given by $\sqrt{(\lambda/L)}$ where λ is the x-ray energy and L , the undulator length.[6] For the upper and lower gap settings, this corresponds to 0.6 and 2 mrad, respectively, for the fundamental. The angular divergence due to the finite particle beam emittance is approximately 0.1 and 0.6 mrad in the horizontal and vertical directions, respectively. Consequently, the effective width of the central cone is dominated by the radiative width except for the closed-gap fundamental in the horizontal direction.

Calculation of the photon flux through a 0.14 mrad x 0.14 mrad pin-hole expected over the spectra range for the two gap settings is given in Fig. 5. The calculations show that at a harmonic, x-ray fluxes of greater than 10^{13} ph/s/0.1%BW can be expected. This is approximately 100 times larger than that achieved on a bending magnet beamline at the VUV ring with the same pin-hole size.

4. Conclusions

The magnetic design of the variable-gap tunable undulator to be installed on the VUV-ring at the National Synchrotron Light Source is in its final stages, and construction of the device should begin soon. The magnetic properties have been optimized to provide enhanced spectral brilliance over a large tunability range which is ten times the energy of the fundamental at the closed gap position. The large flux expected for the device over the soft x-ray range will provide new possibilities for experiments in the areas of spin-polarized photoemission, surface science and materials science.

Acknowledgement

This work was supported by the U.S. Department of Energy, BES-Materials Sciences, under contract No. W-31-109-ENG-38. The undulator development project at NSLS is supported by the ONR under Contract No. N00014-87-F-0022.

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1. K. Halbach, Journal de Physique 44, C1-211 (1983).

2. PANDIRA is an improved version of POISSON which allows solution of permanent magnet and residual error problems. POISSON is a version of TRIM developed by K. Halbach.

3. S. H. Kim, IEEE Trans. on Magnetics, Vol. 24, 1102 (1988).

4. K. Halbach, E. Hoyer, S. Marks, D. Plate and D. Shuman, IEEE Trans. on Nucl. Science, NS-32, 3640 (1985).

5. See, for example, S. Krinsky, M. L. Perlman and R. E. Watson in Handbook on Synchrotron Radiation, Vol. 1a, ed by E. E. Koch, North Holland, 1983, p. 65.

6. K.-J. Kim, Nucl. Inst. Meth. A246, 71 (1986).

Figure Caption

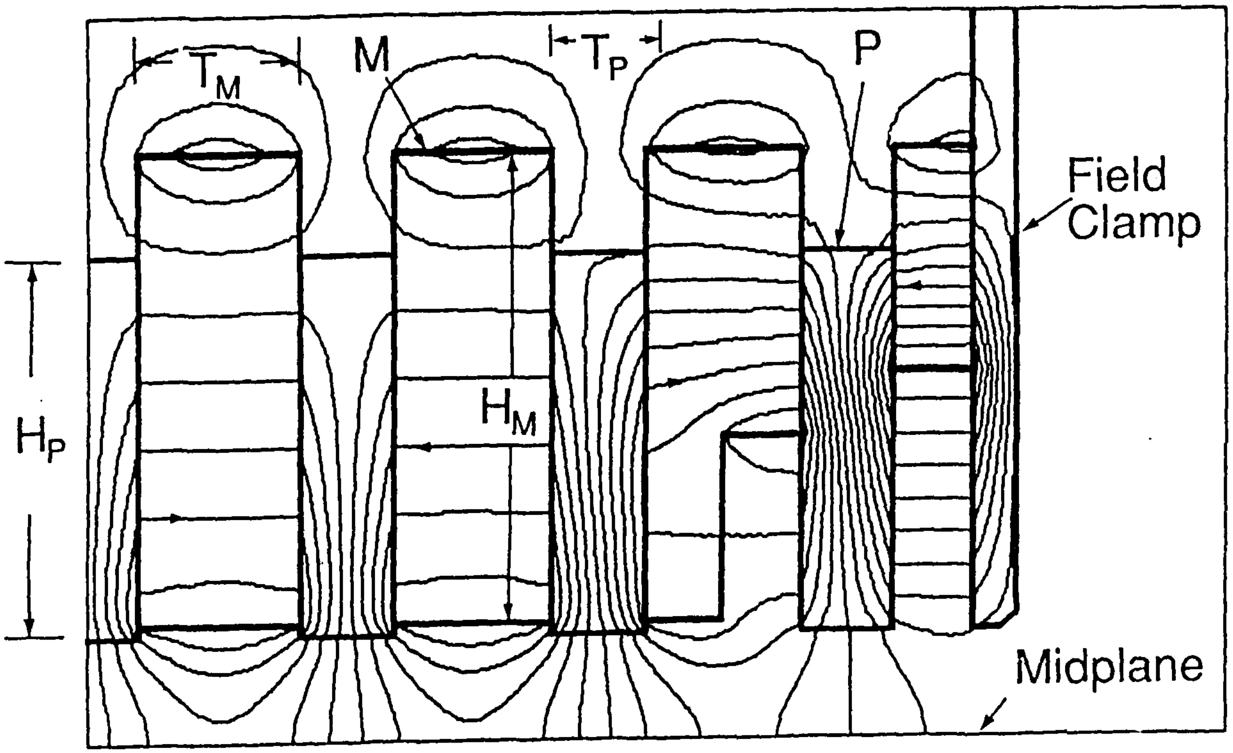
Fig. 1 Horizontal (x) cross section of the upper half of the undulator magnet structure including the end-pole configuration. The flux lines are from a PANDIRA calculation at the minimum gap of 3.4 cm. Here M is Nd-Fe-B magnet and P is vanadium permendur pole. H_M and T_M are the magnet height and thickness and H_p and T_p, the pole height and thickness, respectively.

Fig. 2 Plot of the vertical (y) component of the mid-plane on-axis flux of the undulator near the end pole region at the minimum gap.

Fig. 3 On the on-axis spectral brilliance of the U5 undulator including emittance effects of the VUV ring, at the open (K=1 cm) and closed gap (K=3) positions.

Fig. 4 The spectral brilliance of the fundamental and third harmonic over the entire tunability range.

Fig. 5 The flux through a 0.14 mrad by 0.14 mrad pinhole on axis as a function of photon energy at the open (K=1) and closed (K=3) gap positions.



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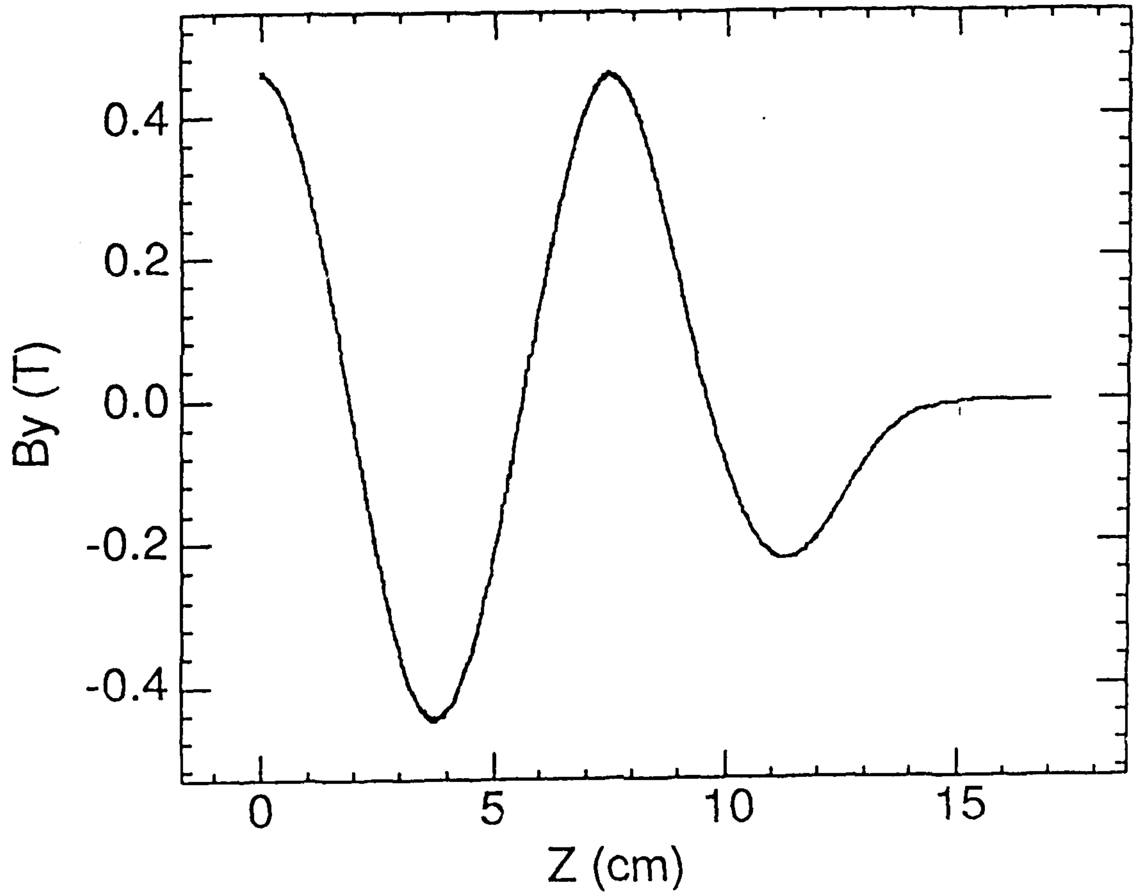
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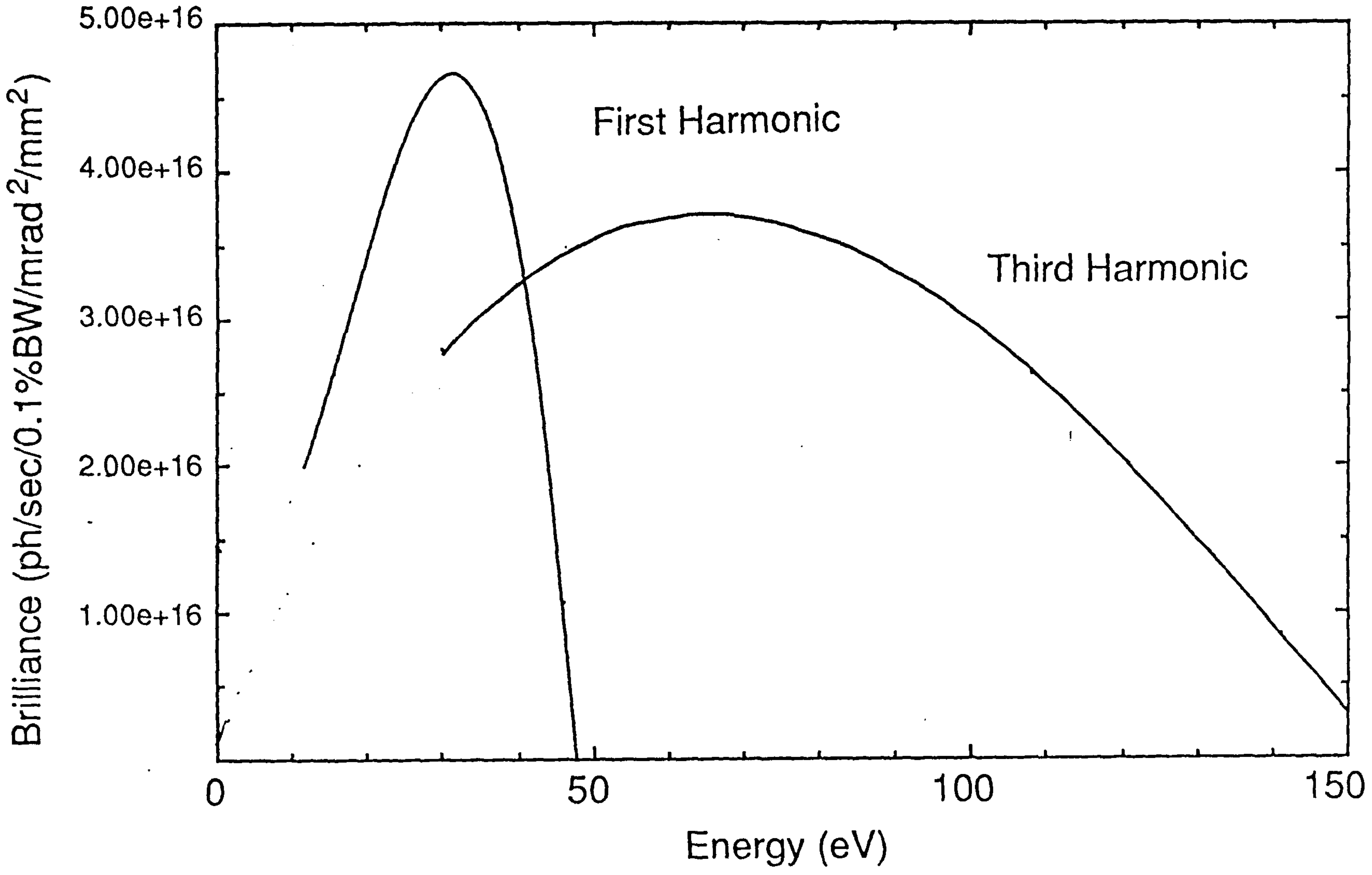
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4.00e+16
3.00e+16
2.00e+16
1.00e+16
Brilliance (ph/sec/0.1%BW/mrad²/mm²)
First Harmonic
Third Harmonic
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100
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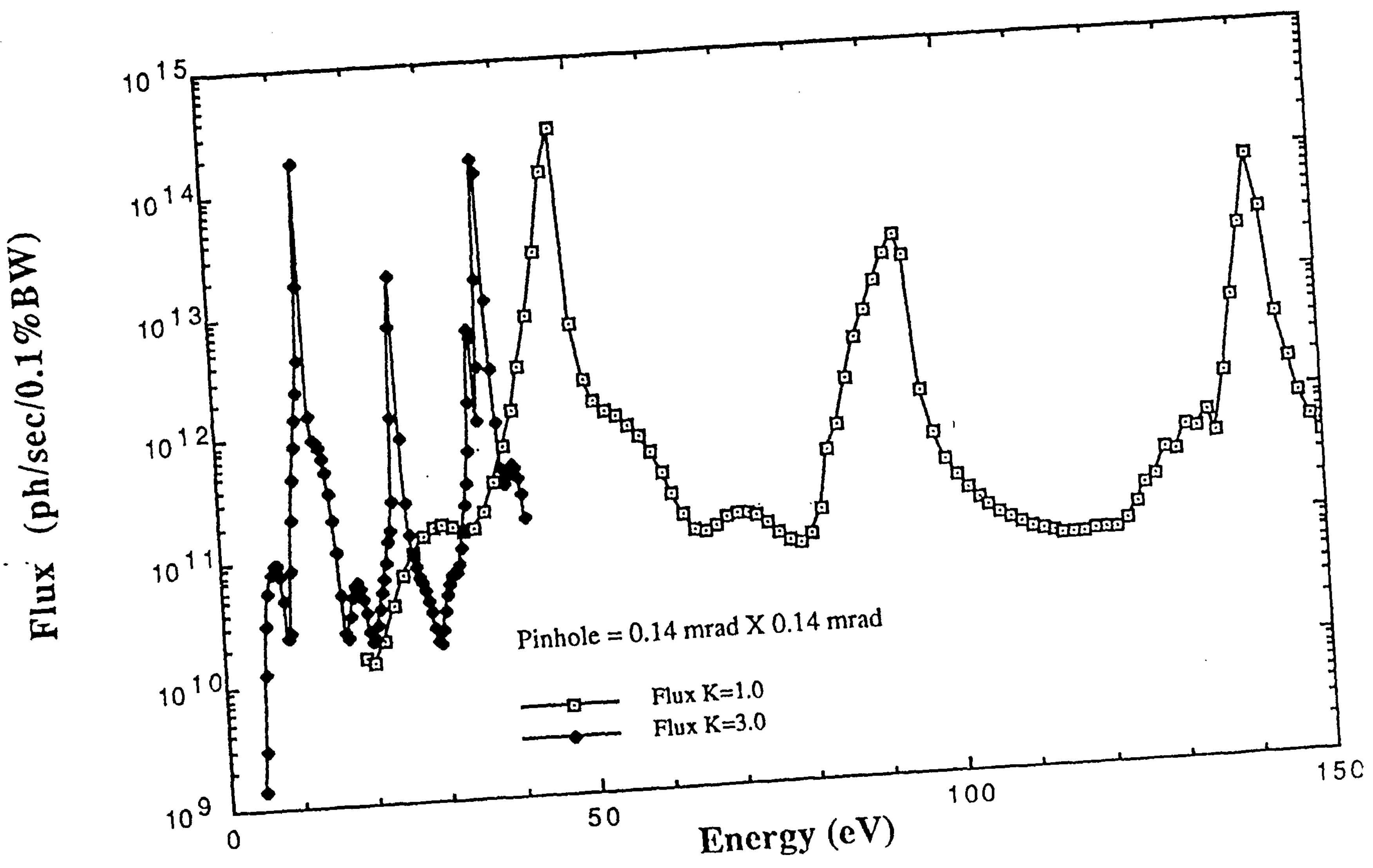
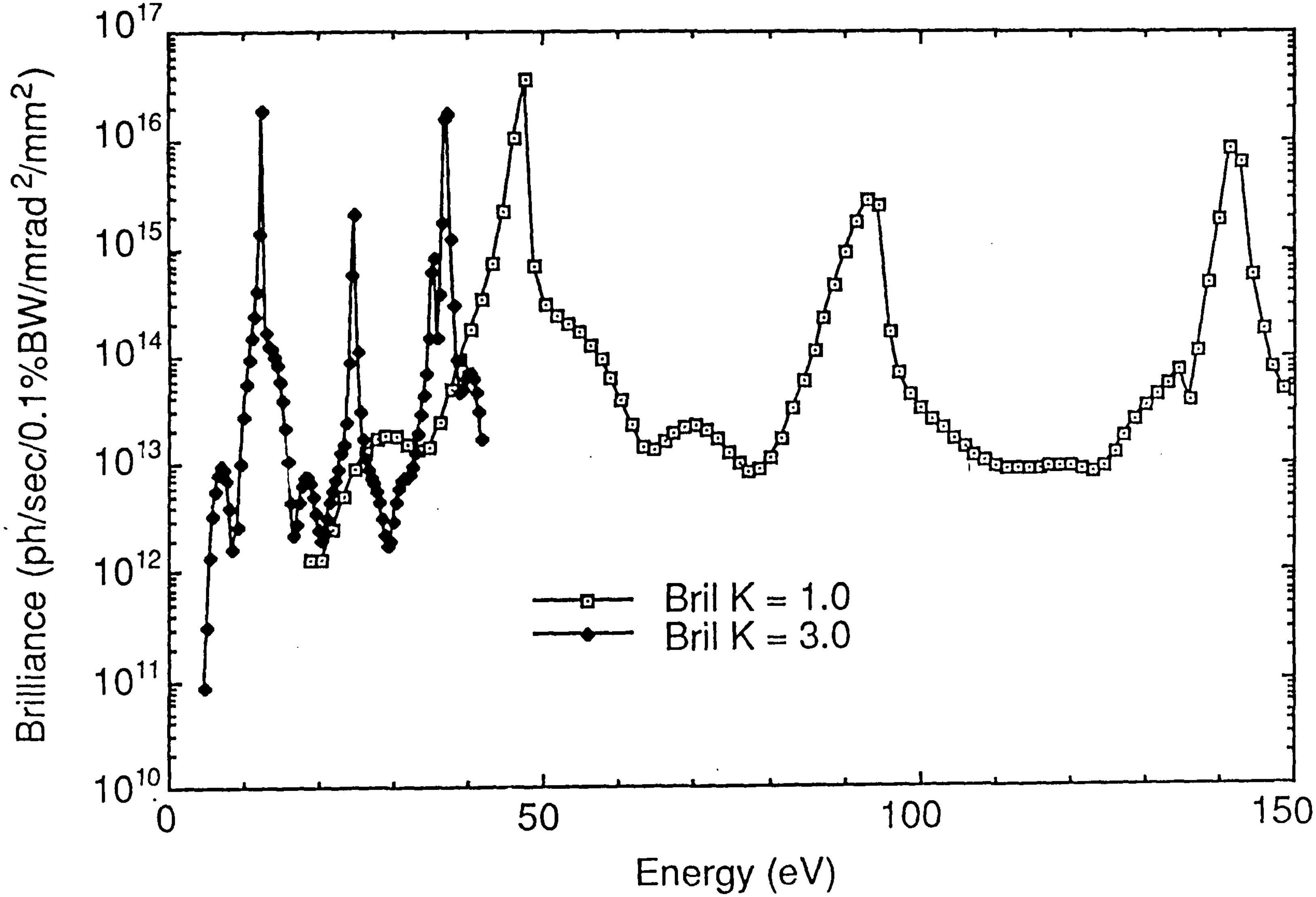
Energy (eV)



Flux (ph/sec/0.1%BW)
10 15
10 14
10 13
10 12
10 11
10 10
10 9
0
50
100
150
Energy (eV)
Pinhole = 0.14 mrad X 0.14 mrad
Flux K=1.0
Flux K=3.0



Brilliance (ph/sec/0.1%BW/mrad²/mm²)
Energy (eV)
Bril K = 1.0
Bril K = 3.0

PREFACE

An international conference on the Vacuum Design of Advanced and Compact Synchrotron Light Sources was held at Brookhaven National Laboratory in May 1988. Co-sponsored by the American Vacuum Society and Brookhaven National Laboratory, its purpose was to bring together physicists, engineers, equipment manufacturers, and users for an exchange of information on state-of-the-art machine design. This book comprises the papers that were presented at this conference.

We would like to acknowledge the contributions from all the authors, the time and effort of the conference planners, the hardworking secretaries for diligently typing the camera-ready manuscripts, and last-but-not-least Sam Bader (ANL) for suggesting the need for this conference.

Editors: H. J. Halama
J. C. Schuchman
P. M. Stefan

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NORTH CAROLINA STATE UNIVERSITY

VACUUM DESIGN OF ADVANCED AND COMPACT SYNCHROTRON LIGHT SOURCES

UPTON, NY 1988

EDITORS:
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& P. M. STEFAN
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